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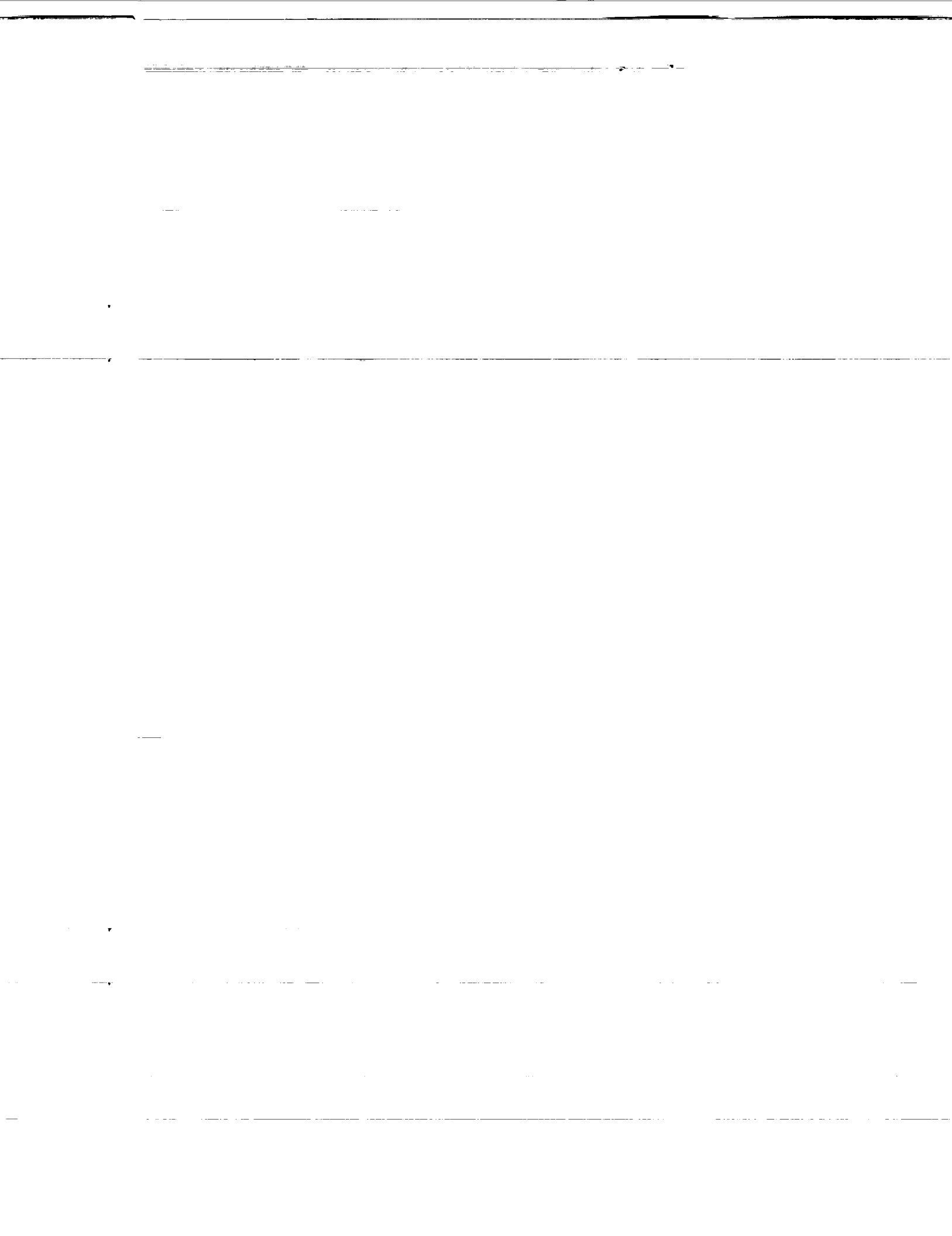26527

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Effect of Tabs on the Evolution of an Axisymmetric Jet

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SUMMARY

The effect of vortex generators, in the form of small tabs at the nozzle exit, on the evolution of an axisymmetric jet was investigated experimentally, over a jet Mach number range of 0.34 to 1.81. The effects of one, two and four tabs were studied in comparison with the corresponding case without a tab. Each tab introduced an "indentation" in the shear layer, apparently through the action of streamwise vortices which appeared to be of the "trailing vortex" type originating from the tips of the tab rather than of the "necklace vortex" type originating from the base of the tab. The resultant effect of two tabs, placed at diametrically opposite locations, was to essentially bifurcate the jet. The influence of the tabs was essentially the same at subsonic and supersonic conditions indicating that compressibility has little to do with the effect.

INTRODUCTION

Tabs, or small protrusions in the flow at the exit plane of a nozzle, have long been known to reduce screech noise from supersonic jets (Tanna, 1977). Bradbury & Khadem (1975), to our knowledge, were the first to make flow field measurements for a subsonic jet under the influence of tabs. The tabs were found to increase the jet spread rate significantly. Ahuja & Brown (1989) recently conducted a series of experiments on the effect of tabs on supersonic jets, and reached a similar conclusion in regards to the effect on the flow field. With support from NASA Lewis, the latter investigators continued to study the effect on rectangular jets as well as on the noise radiated from the jet (Ahuja et al., 1990). In terms of the plume reduction i.e., a faster spreading of the axisymmetric jet, the effect of the tabs was so dramatic that the technique has been at times referred to as the "supermixer" (E.J. Rice, private communication). However, the flow mechanisms, even the basic changes in the flow field caused by the tabs, essentially remained unknown.

The obvious technological significance of the ability to increase mixing and reduce noise, even in supersonic jets, provided a strong motivation to pursue the topic further. This led to the present investigation. A detailed flow visualization experiment was conducted together with quantitative measurements of the flow field. Even though questions have remained unresolved, the results provided a clearer insight into the flow field changes caused by the tabs. This is what we would like to describe in this paper. Preliminary results of the experiment were reported by Samimy, Zaman & Reeder (1991). Only key results are discussed here due to space limitation; a more detailed paper is being prepared for Journal submission.

EXPERIMENTAL FACILITY

The experiments were carried out in a small supersonic jet facility at NASA Lewis Research Center. The facility is schematically shown in figure 1. A converging-diverging nozzle with throat diameter of 0.635 cm and design Mach number of 1.36 was used. The Mach number range covered was 0.34 to 1.81, representing subsonic and over- and underexpanded supersonic conditions. The flow visualization pictures were obtained by laser sheet illumination and Schlieren photography. A 4 W argon-ion laser was used for both techniques. The laser sheet illumination was performed in the supersonic jets without any seeding. The cold supersonic jet core caused natural moisture condensation in the mixing layer from the entrained ambient air. Thus, with this technique, the mixing layer region was illuminated.

A gated double-intensified CCD camera was used to record successive images on a video tape. Standard hot-wire measurements were performed for the subsonic jets. At a jet Mach number of 0.34, hot-wire surveys indicated a flat mean velocity profile with a "nominally laminar" boundary layer at the nozzle exit. The boundary layer state for the supersonic regime remains unknown, but is also likely to be "nominally laminar." For the supersonic jets, a 0.8 mm (od) pitot tube was used to measure total pressure. A special 1 mm (od) static pressure probe, designed after Seiner & Norum (1979), was used to measure the static pressure only on the jet centerline. Probe traverses and data acquisition were done remotely under computer control.
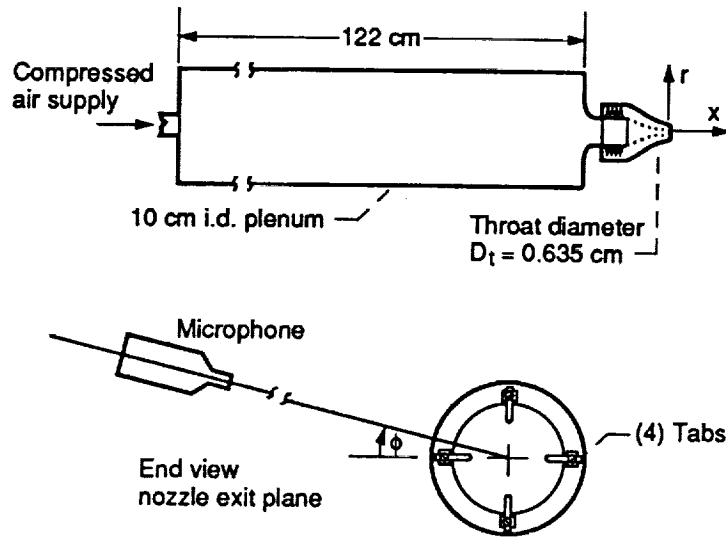

Figure 1.—Schematic of flow facility.

RESULTS AND DISCUSSION

The notations p_t and p_a are used to denote the stagnation pressure and the ambient pressure, respectively; p_{to} denotes stagnation pressure in the plenum chamber. The design Mach number, 1.36 corresponded to a pressure ratio, p_a/p_{to} = 0.3323. For any given plenum pressure p_{to}, the notation M_j is used to denote the Mach number had the flow expanded to ambient pressure. In the supersonic regime, pressure ratios $0.3323 < p_a/p_{to} < 0.661$ produced overexpanded jets and $p_a/p_{to} < 0.3323$ produced underexpanded jets. Thus, overexpanded condition existed for $0.79 < M_j < 1.36$, and the flow was underexpanded for $M_j > 1.36$. In the range $0.7 < M_j < 0.79$ ($0.661 < p_a/p_{to} < 0.72$), a normal shock would be expected to occur in the diverging section of the nozzle. The static pressure is denoted by P, P_e representing that at the nozzle exit.

Flow Field Data

Figure 2 shows the measured stagnation pressure for eight M_j as indicated. In this and later figures, pairs of curves have been shifted by one major ordinate division, in order to present the data in a concise manner. Each pair in figure 2 contains data for the 2-tab case and the corresponding no-tab case. The data have been normalized by the respective plenum pressure, p_{to}.
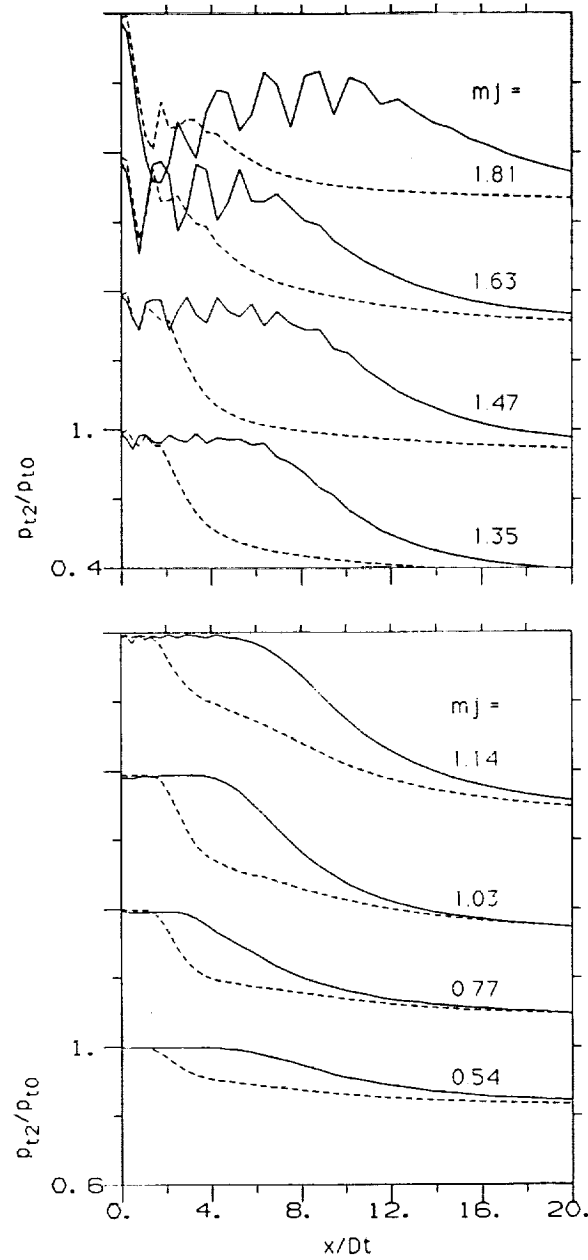
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Figure 2.—Centerline variation of stagnation pressure for the eight M_j : ———, no tab; --------, 2-tab. Successive pairs of curves are staggered by one major ordinate division.

In the supersonic regions of the flow, the measured stagnation pressure, p_{t2}, corresponds to the stagnation pressure behind the standing bow shock in front of the pitot probe. The oscillations in the data near the jet exit are due to the standing shock structure. Let us emphasize that due to probe interference there is measurement error and the data in the supersonic regions should be considered only qualitative. However, the data are accurate enough to capture the global features; for example, the number of shocks and their spacings are captured quite well as indicated by comparison with Schlieren photographs discussed later.

It is evident from figure 2 that the effect of the tabs is similar over the entire M_j range. Note that in the supersonic regime, the shock structure is affected drastically by the tabs. This is accompanied by elimination of screech noise for which data have been presented by Samimy, Zaman & Reeder (1991).

In order to calculate the local Mach number, one needs to measure, besides p_{t2}, either the static pressure before, P_1, or the static pressure after the shock, P_2. In an over- or underexpanded supersonic jet, there is a complex shock/expansion system in the flow itself and it is not an easy task to measure either P_1 or P_2. The double-cone static pressure probe, designed after Seiner & Norum (1979), was fabricated and used only to measure P_1 on the jet centerline. Figure 3 shows the P_1 distributions corresponding to the eight M_j values of figure 2. For these data, essentially similar comments can be made as done for the p_{t2} data of figure 2 including on the measurement accuracy. Note that even for the subsonic jet at the lowest M_j, the static pressure is negative over a long distance along the centerline; a similar result was reported by Hussain & Clark (1977).
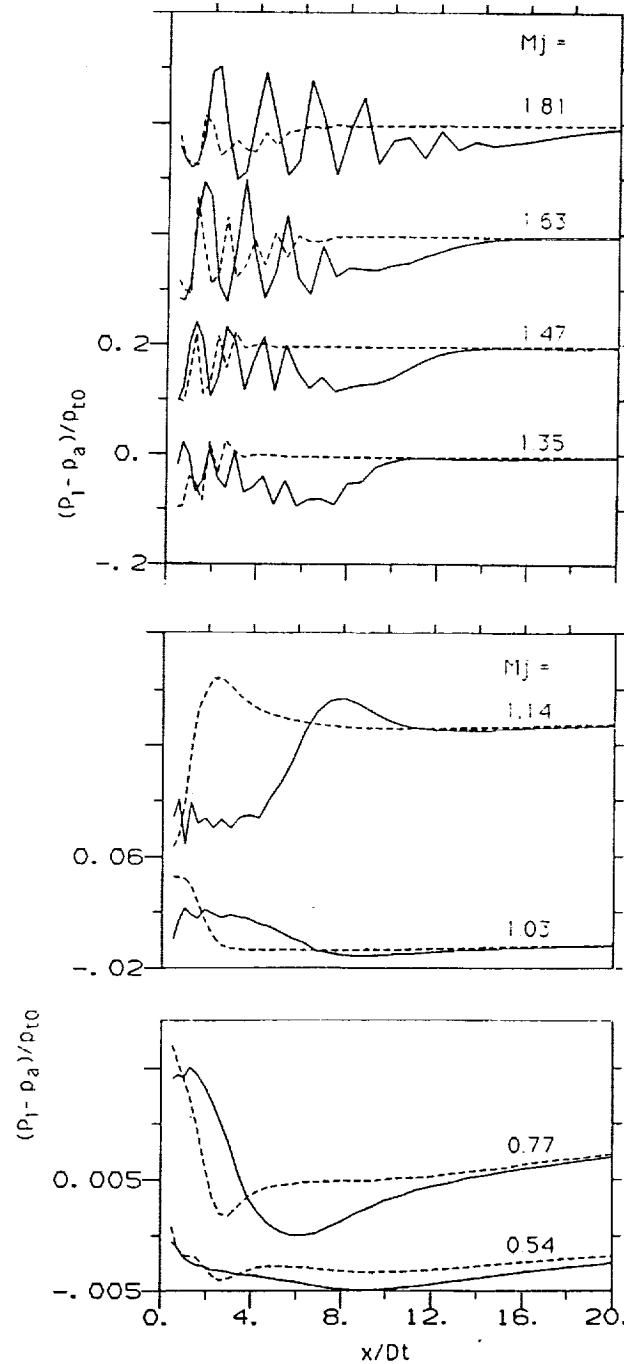

Figure 3.—Centerline variation of static pressure for the eight M_j shown similarly as in figure 2.

The P_t and p_{t2} data were combined to calculate the local Mach number variation along the jet axis. Data for $M_j = 1.63$ are shown in figure 4 comparing the 1-, 2- and 4-tab cases with the no-tab case. Again, it is clear that the shock/expansion pattern is drastically affected by the tabs. One also finds that while just one tab affects the flow field drastically, effects of two and four tabs are more pronounced.

Data for the centerline variation of the mean velocity, measured with a hot-wire at $M_j = 0.34$, are presented in figure 5. Clearly, the potential core of the jet is reduced drastically and a similar inference is made, as with figure 4, in regards to the effect of the number of tabs.

While the data of figures 4 and 5 show the mean velocity distribution only along the jet centerline, detailed data on radial profiles and far-field noise were also obtained but are not included here. These data showed that four tabs resulted in the most reduction of the far-field noise. However, although four tabs resulted in more initial mixing, as evident from mass flux computed from the radial profiles, the effect of two tabs persisted the farthest downstream. This also becomes evident from the flow visualization results.
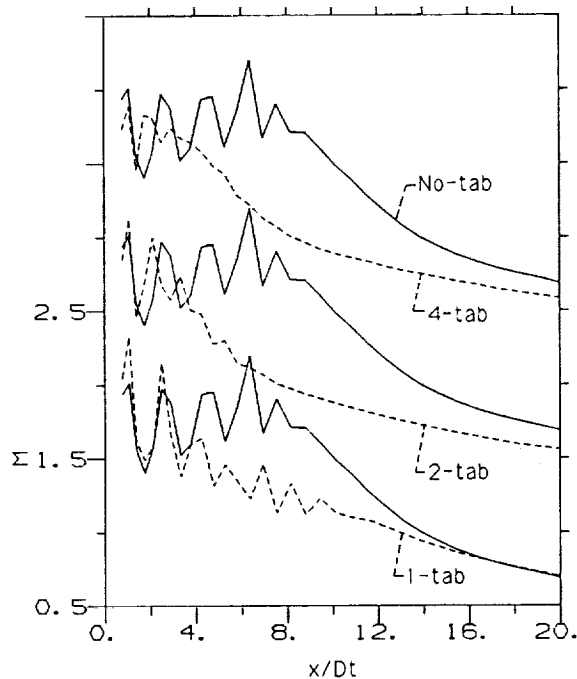
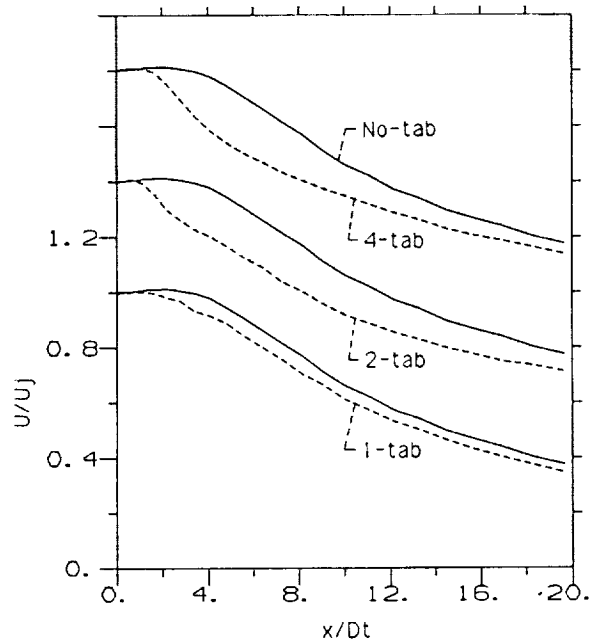Figure 4.—Centerline variation of Mach number for M_j = 1.63 with and without tabs.

Figure 5.—Centerline variation of mean velocity for M_j = 0.34 with and without tabs.

Flow Visualization

Figure 6 shows long exposure Schlieren photographs of the flow field for five M_j as indicated. The flow is from left to right and the pictures were obtained using a vertical knife-edge, visualizing the density gradients in the streamwise direction. The flow fields approximately cover x/D_t range of 0 to 13. The knife-edge position was changed for fine adjustments from case to case; thus, the visual jet width should not be considered as a measure of jet spread. In figure 6(a), flow fields without any tab are shown. The shock spacing increases with increasing M_j in the supersonic regime. Note that the shock spacings, for example at $M_g = 1.81$, are found to be the same as observed in the p_{t2} and P_t measurements (figs. 2 and 3). About six shock cells are observed consistently within a x/D_t range of 0 to 12.

Figure 6(b) shows corresponding photographs of the flow field with two tabs, when viewed parallel to the plane containing the two tabs. It is clear that the jet bifurcates in the plane perpendicular to the tabs, at all M_j. In the supersonic regime, the shock spacings have also been significantly reduced (compare with figure 6(a)). When viewed perpendicular to the plane containing the two tabs, only one part of the bifurcated jet is seen and thus the jet spread appears less, and these data are not shown. Note that the effect for the overexpanded case at $M_j = 1.14$ (fig. 6(b)) appears less than that at other M_j; this point is addressed in the following section.
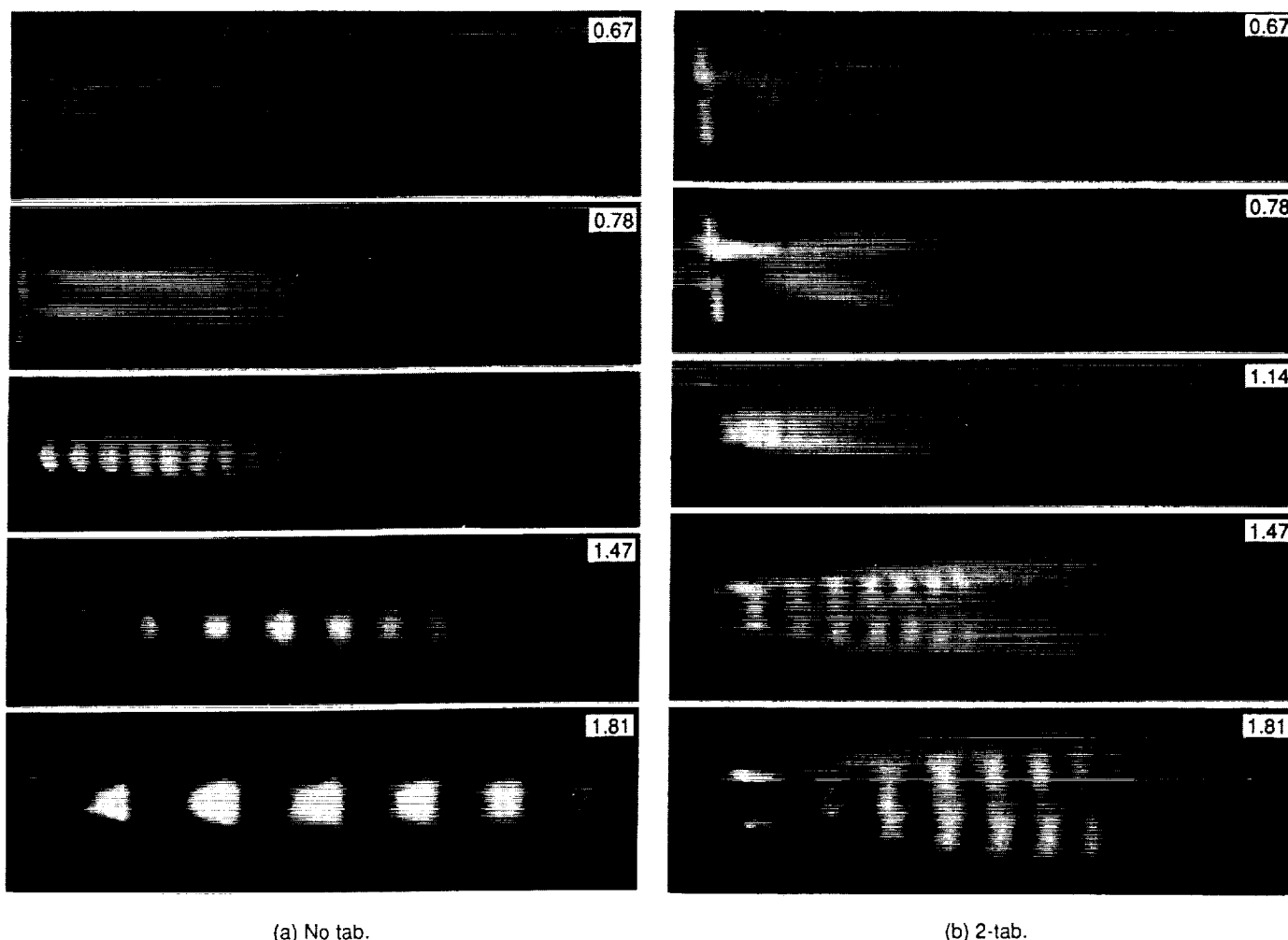
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(a) No tab.

(b) 2-tab.

Figure 6.—Schieren photographs of the jet at indicated M_j, approximate x/D_t range is 0-13.

The bifurcation of the jet observed in figure 6(b) is commensurate with the radial velocity profiles obtained presently (Samimy, Zaman & Reeder, 1991) as well as by Ahuja & Brown (1989) and Bradbury & Khadem (1975). Ahuja et al. (1990) presented a set of Schlieren data for an underexpanded case that appeared the same as those for the underexpanded cases of figure 6(b). The bifurcation effect resembles the effect achieved by dual mode helical acoustic excitation (Parekh, Reynolds & Mungal, 1987), or by simple lateral vibration of the nozzle issuing the jet (Andrade, 1941).

Laser sheet visualization of the mixing region was performed for the supersonic jets. Figure 7(a) shows the jet cross section at four different axial locations for the natural jet at $M_j = 1.63$. The bright and initially narrow ring shows the mixing layer, which is growing with the streamwise distance eventually covering the entire cross section of the jet. The departure from axisymmetry in these pictures is mainly due to the camera angle. Corresponding pictures for the flow field with 1, 2 and 4 tabs are shown in figures 7(b) to (d), respectively. Again, the camera needed to be adjusted from picture to picture and thus the visual cross sections do not represent the jet spread.

The presence of a tab significantly distorts the mixing layer. The effect is to leave an "indentation" or a bulge into the high speed side which grows and persists far downstream. In a recent experiment using laser sheet illumination, Clemens & Mungal (1991) studied distortions in a plane, compressible mixing layer, produced by shocks originating from the wind tunnel side wall. The distortions reported had curious similarities with the present case, although it appeared that the "bulging" occurred on the lower speed side of their mixing layer. Possible vorticity dynamics producing the distortions in the present case are discussed in the next section.

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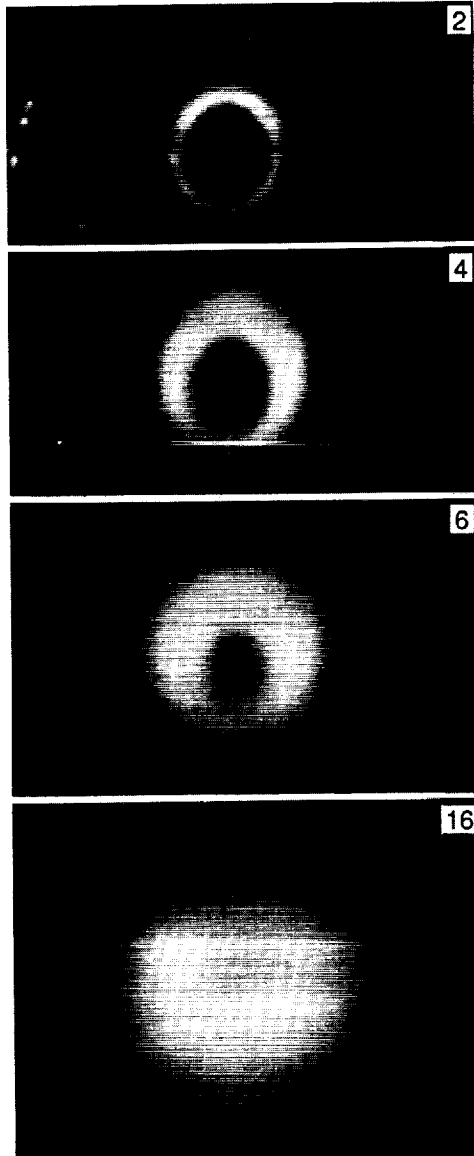
(a) No tab.
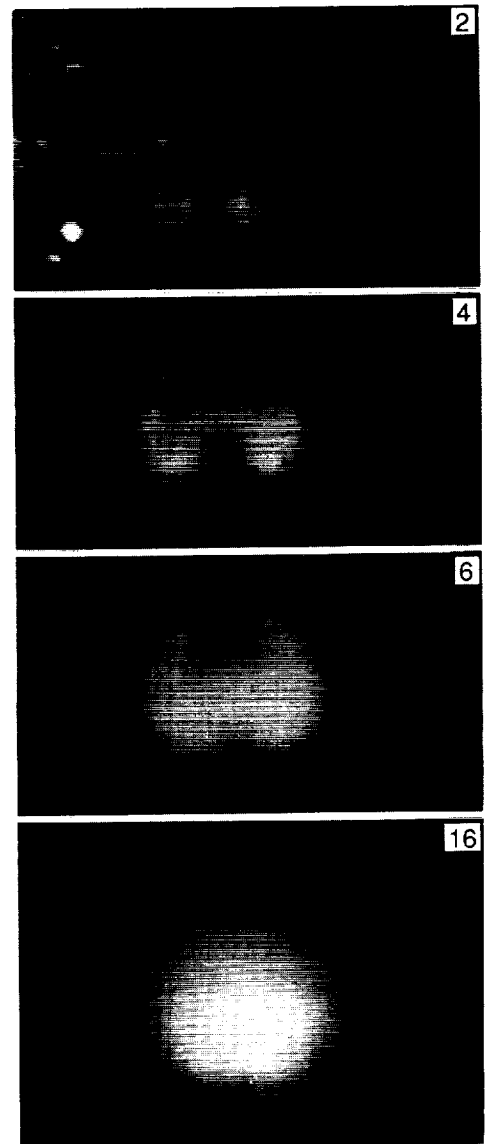
(b) 1-tab.

Figure 7.—Laser sheet illuminated cross section of the jet, at indicated x/D_t. $M_j = 1.63$.
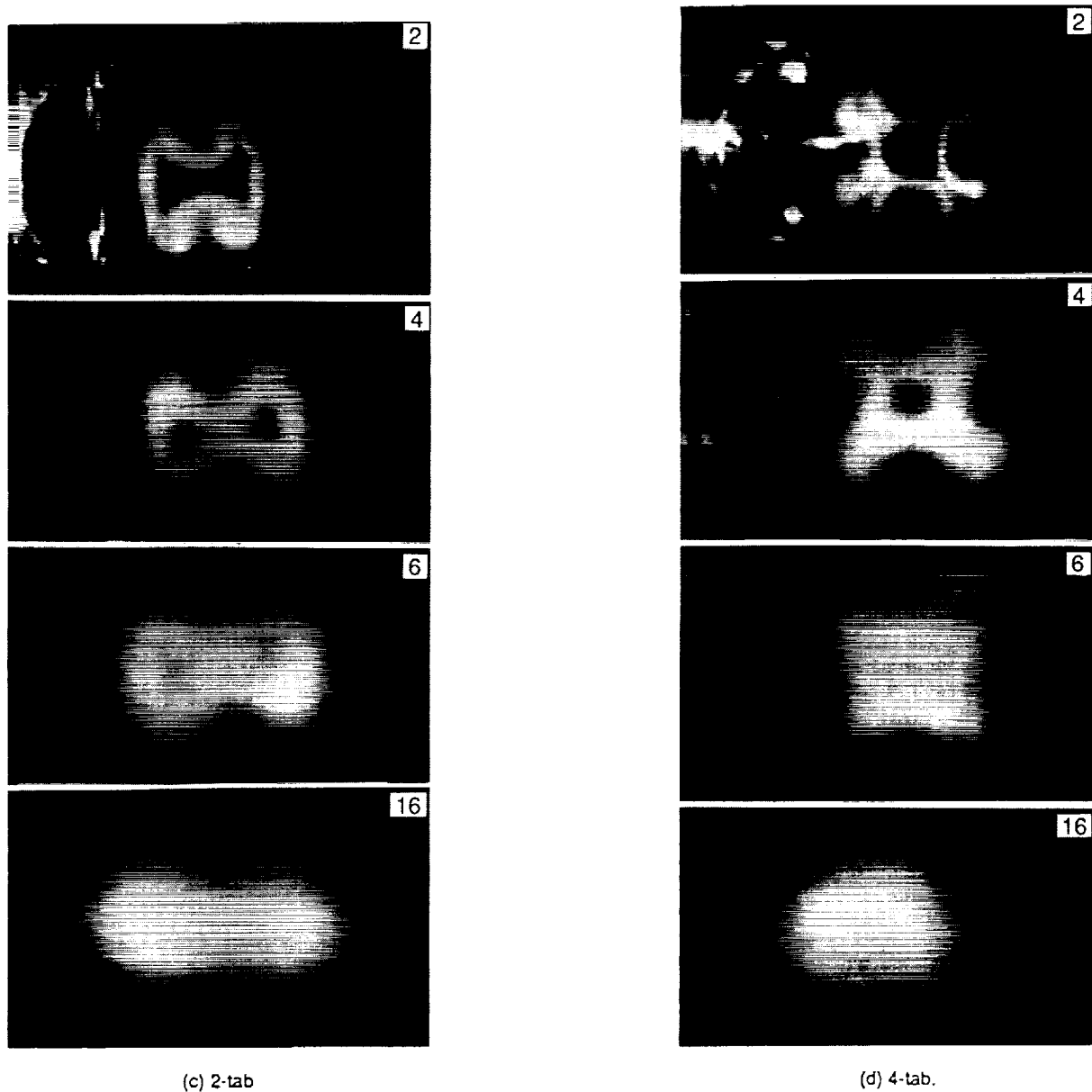
(c) 2-tab

(d) 4-tab.

Figure 7. - Concluded.

In figure 7, while the jet has regained the axisymmetric shape for the 1- and 4-tab cases by $16D_t$, it has remained quite elongated in the plane perpendicular to the tabs for the 2-tab case. In fact visualization at $30D_t$ for the 2-tab case still shows a very elongated cross section; this is shown in figure 8 for $M_j = 1.81$.

The initial evolution of the mixing layer under the action of two tabs is further shown in figure 9(a). It is clear that each tab produces a large distortion in the mixing layer which grows with downstream distance and results in a bifurcation of the jet by about $3D_t$. Figure 9(b) further documents the effect of two tabs at $x/D_t = 1.5$ for three M_j. Within the range covered, the effect apparently becomes more pronounced with increasing M_j. With increasing M_j the jet core temperature becomes lower, thus, with the technique used for the visualization, the mixing layer may be expected to appear sharper. However, there is also a diminishing effect of the tabs with decreasing M_j as the overexpanded condition is approached. A possible reason for this behavior is addressed in the following section.
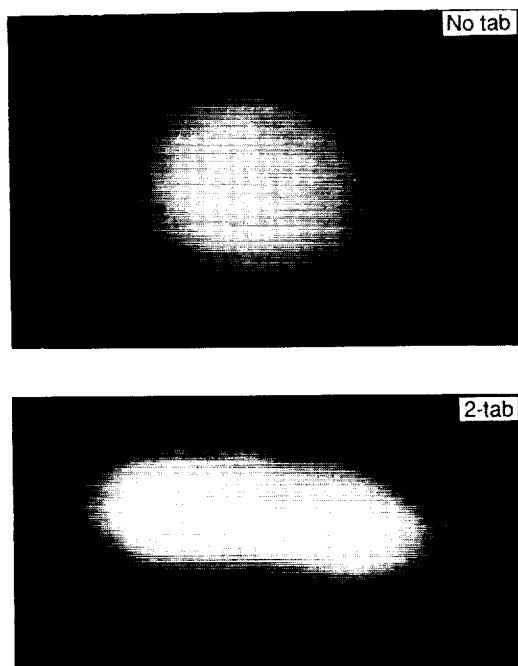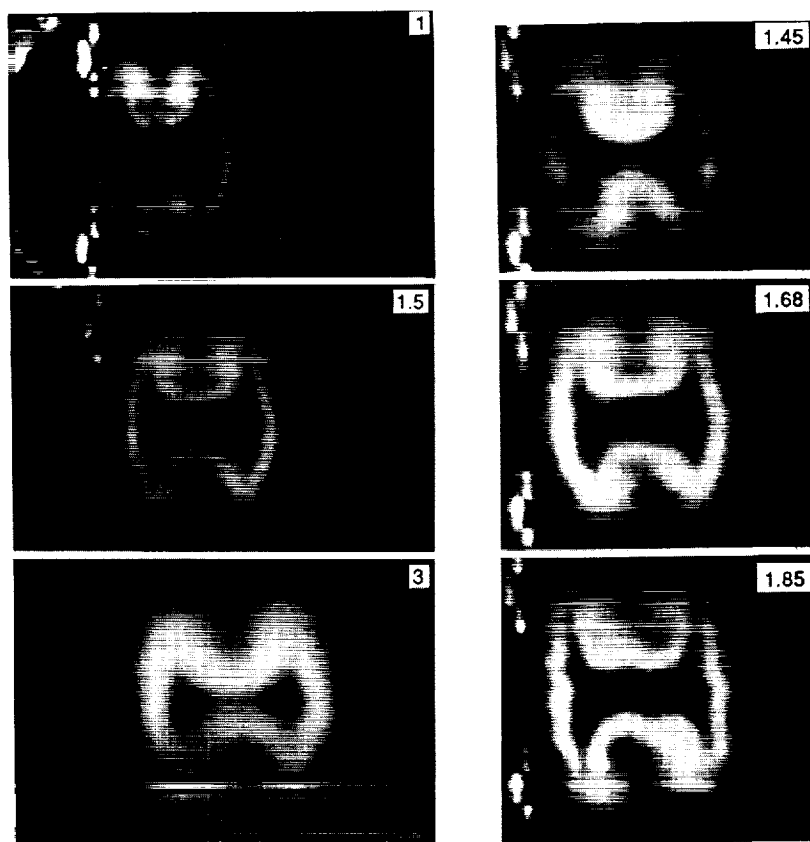
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Figure 8.—Jet cross section at x/D_t = 30, M_j = 1.81.

(a) At indicated x/D_t, M_j = 1.63.

(b) At indicated M_j, x/D_t = 1.5.

Figure 9.—Effect of two tabs.

DISCUSSION AND CONCLUDING REMARKS

An inference that can be made from this investigation is that compressibility may have little to do with the effect of the tabs. The data show essentially the same effect all the way from incompressible to highly underexpanded supersonic conditions. The tabs, however, do weaken the shock structure drastically in the supersonic cases, which is accompanied by elimination of the screech noise. But the basic effect must originate from changes in the vorticity distribution caused by the tabs.

Perhaps, the most illuminating results are the laser sheet visualization pictures of figures 7 to 9. The "indentation" in the mixing layer may not be a "passive" wake of the tab. Similar flow visualization pictures (not shown here) in certain overexpanded cases, where the tabs were essentially ineffective, showed that the wake from the tab almost vanished by about two jet diameters. The jet mixing layer in these cases appeared essentially oblivious to the presence of the tabs. In contrast, the flow field is about 50 tab widths downstream, at $4D_i$ in figure 7(c), yet the distortion appears to be growing and influencing the entire jet cross section. The distortions introduced by the tabs are also not an artifact of the visualization technique. Radial profiles of Mach number confirmed the distortions. This leads us to believe that there must be a significant interaction between the flow field over a tab and the sheet of azimuthal vorticity that emanates from the nozzle. The following is a conjecture in regards to the vorticity dynamics.

It is likely that a pair of counter-rotating streamwise vortices are shed from each tab as sketched in figure 10(a). This should be a "stationary" vortex and not like "hairpin" vortices which are shed periodically (Acarlar & Smith, 1987). This is because the photographs in figures 7 to 9 are images with a long time exposure where any periodic structure would be averaged out. The streamwise vortices interact and evolve with the azimuthal sheet of vorticity issuing from the nozzle. The resultant vorticity distribution on a cross-sectional plane may be expected to be as in figures 10(b) and (c) for one and two tabs, respectively.

(a) Streamwise vortex pair from a tab.

(b) Vorticity distribution for 1-tab.   (c) Vorticity distribution for 2-tab.

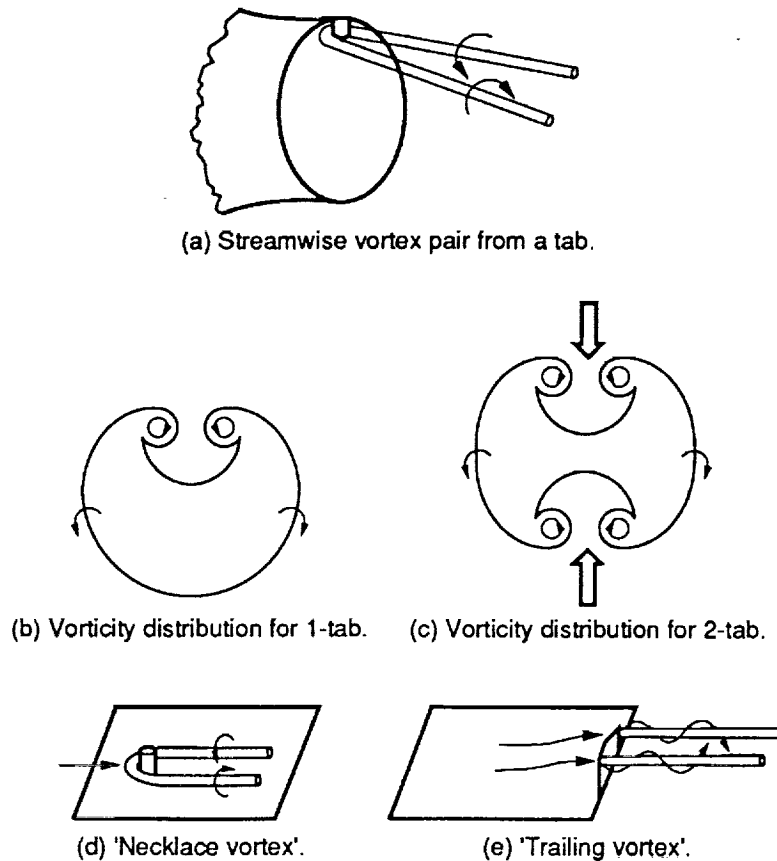(d) 'Necklace vortex'.   (e) 'Trailing vortex'.

Figure 10.—Likely vorticity dynamics.

The strength of the streamwise vortices should eventually decrease to leave only the "indentations" on the mixing layer as observed at $x/D_i = 3$ in figure 9(a). Farther downstream, the bifurcation of the jet may take place in a similar manner as suggested by Hussain and Husain (1989) through what they called a "cut-and-connect" process. In fact, these investigators observed a very similar sequence of deformations leading to a bifurcation of a jet originating from an elliptic nozzle.

The question then arises as to the origin of the counter-rotating vortex pair sketched in figure 10(a). Such "stationary" vortex pairs, formed over protuberances in boundary layer flows, have been variously called a "horseshoe" vortex or "necklace" vortex (Acarlar & Smith, 1987; Bandyopadhyay & Watson, 1988). However, a little scrutiny should indicate that the vortex sketched in figure 10(a) is not the same. A necklace vortex is sketched in figure 10(d), following Bandyopadhyay & Watson (1988). The sense of rotation in this case is contrary to what is sketched in figure 10(a). Lin, Selby & Howard (1991) recently investigated the flow over various vortex generating devices while studying their effect on boundary layer separation. It is interesting that they reported pairs of streamwise vortices from several of these devices to be of the same sign as found here for the tabs.

It is possible that the tab acts as a "winglet" and produces a pair of "trailing vortices." This is sketched in figure 10(e), which is similar to the trailing vortices originating from the tips of a wing (e.g., Van Dyke, 1982, p. 51). It should be recognized that in order for the tip vortices to form, the wing should be at an angle of attack producing a resultant lift. The tabs, however, are projected normally into the flow. It is plausible that the boundary layer upstream of the tab is lifted up so that the approaching streamlines are at an angle of attack with respect to the tab producing a resultant force acting radially and away from the jet axis. In such a case, the pair of counter-rotating vortices as sketched in figure 10(e) would be quite realistic.

One may further conjecture that the mechanism of streamwise vortex generation from the "ramps" of Bradbury & Khadem (1975) and from the "wishbones" or "doublets" of Lin, Selby & Howard (1991) are essentially the same as described for the tab. It seems that a triangular shaped tab with the base on the nozzle wall may act similarly (Rogers & Parekh, 1990). However, if this is placed like a "delta wing," with the apex leaning upstream, it seems that vortices of sign opposite to what is sketched in figure 10(e) will be produced. If it is possible to produce such a vortex pair, the "indentation" would be outward into the low speed side of the mixing layer. It is not completely clear if this would really be the case and what the resulting effect would be on the jet evolution.

The suggested streamwise vorticity generation is therefore a pressure driven and inviscid phenomenon and not due to wrapping of the viscous boundary layer around the tab. In order for the tab to work, a favorable pressure differential must exist across the tab. It was observed that in the overexpanded cases the effect of the tab was either less or absent. In the overexpanded case, there is an adverse pressure gradient within the diverging section of the nozzle prior to the exit. In severe cases of overexpansion this could even result in a boundary layer separation. It is, therefore, not surprising that the tab does not work in the overexpanded case because the pressure differential across the tab is either diminished or adverse.

Questions have remained in regard to the optimum geometry of the tab. Further investigation is required to determine the optimum height of the tab relative to the boundary layer thickness. If the vorticity dynamics are correct, as conjectured above, then the width of the tab would also be a critical dimension as that determines the spacing of the two counter-rotating vortices; this needs to be studied further. It also remains to be demonstrated if the tabs will work in jets with a fully turbulent exit boundary layer and a highly disturbed core flow condition, as expected in a practical jet. These issues need to be sorted out before the method could be understood clearly and applied successfully in practice.

ACKNOWLEDGEMENT

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16. Abstract

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